

Effect of power interchange operation of multiple household gas engine cogeneration systems on energy-saving

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ABSTRACT

The effect of power interchange operation of multiple household gas engine cogeneration systems (H-GCGS) on the energy-saving is investigated using an optimization approach based on the mixed-integer linear programming. In this power interchange operation, electricity generated by H-GCGS is shared among households in a housing complex without transmitting to a commercial electric power system so that the operating time of these systems may increase. This paper numerically analyzes optimal operational strategies for 20 households and three types of household energy supply configurations: the power interchange operation of the H-GCGSs (IC), stand-alone operation of each H-GCGSs (SA), and conventional energy supply system without the H-GCGSs. A numerical result clarifies the effectiveness of the power interchange operation from the energy-saving viewpoint and a dominant parameter for evaluating the energy-saving effect.

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1. Introduction

Cogeneration systems have been increasingly utilized for industrial and commercial applications because of their high energy-saving and economic efficiencies. Owing to recent developments of small-scale prime movers with high performance including gas engines (GE), fuel cells, and stirling engines, their applications have been extended to households [1]. Most of operating household cogeneration systems adopt GEs because of their low cost and high reliability.

The energy-saving effect by utilizing household gas engine cogeneration system (H-GCGS) has been studied. Paepe et al. reported the energy-saving effect of 4.7 and 5.5 kW H-GCGSs that are operated at a detached house and terraced family house in Belgium [2]. Cockroft and Kelly reported that an H-GCGS meeting the maximum heat demand in a household needs to operate with overall efficiency of more than 80% for energy-saving [3]. Furthermore, Hawkes and Leach reported the CO₂ reduction effect through an analysis of optimal operational strategy of 2 kW H-GCGS [4]. In these studies, the H-GCGSs can transmit surplus electricity to commercial electric power systems; thus, the H-GCGSs can operate to meet heat demand

variations and do not need storage tanks (STs). However, in Japan, electricity generated by household cogeneration systems cannot be transmitted to commercial electric power systems by the regulation. Therefore, H-GCGSs for Japanese household are downsized and generate electricity at a rating of approximately 1 kW [5,6]. These systems have an operational restriction that they can operate only when the electricity demand of each household exceeds the generated electricity at the rating. This is because they must adopt on-off operation that implies either rated load operation or shutdown due to the inefficiency of their partial load operations [7]. Moreover, a ST must be installed for intermittent hot water supply under this operational restriction; however, heat loss from the ST is considerable when the operating period of the H-GCGS is much different from the high demand period of hot water. Therefore, actual energy-saving effect of the H-GCGSs in Japan is considered to underachieve. To overcome this problem, the capacity of the GE can be further reduced; however, this is not effective because generating efficiency of a smaller scale GE markedly decreases.

Based on this background, the authors propose power interchange operation of multiple H-GCGSs in a housing complex. In this operation, electricity generated by the H-GCGSs is shared among households in the housing complex without transmitting to an external commercial electric power system. Since the surplus electricity generated at a household with little electricity demand can be transmitted to other households that have much electricity demand, the aforementioned their operational restriction is

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Nomenclature

E	electricity [kWh/h]
F	natural gas consumption [m^3/h]
J	objective function (daily primary energy consumption) [MJ/d]
K	number of sampling times
k	index for sampling times
M	number of representative days
m	index for representative days
N	number of object households
n	index for object households
p, q, r, s	performance characteristic values [kWh/h, m^3/h , (MJ/h)/(m^3/h), kWh/h]
Q	heat flow rate [kWh/h]
S	stored heat [MJ]
Δt	sampling time interval [h]
α	reduction rate in total daily primary energy consumption [%]
δ	binary variable for expressing on-off status
η_L	heat loss rate of storage tank [%/h]
$(\)$	upper limit

Abbreviation (subscript)

CO	conventional energy supply system
GE	gas engine
GW	gas-fired water heater
H-GCGS	household gas engine cogeneration system
IC	power interchange operation of household gas engine cogeneration systems
SA	stand-alone operation of each household gas engine cogeneration system
ST	storage tank
THPR	total daily heat to power demand ratio of object households

Superscript

a	auxiliary machine
in	inlet
out	outlet

power interchange operation is expected to increase their energy-saving effect.

This paper discusses the energy-saving effect of the power interchange operation as the first step of its feasibility study. To clarify theoretical limit of the energy-saving effect, operational strategies of multiple H-GCGSs are numerically analyzed by an optimization approach based on the mixed-integer linear programming. The analysis is conducted for 20 households and three types of household energy supply configurations: the aforementioned power interchange operation of the H-GCGSs, stand-alone operation of each H-GCGS, and conventional energy supply system without the H-GCGS. Through a numerical analysis of the operational strategies, effectiveness of the power interchange operation from the energy-saving viewpoint, and a dominant parameter for evaluating the energy-saving effect are clarified.

2. System configuration

Fig. 1 shows a schematic diagram of power interchange operation of multiple H-GCGSs in a housing complex (IC). Each household in a housing complex installs the H-GCGS, a ST, and a gas-fired water heater (GW). The solid, dash-dotted, and dotted lines in this figure show the flows of hot water, electricity, and natural gas, respectively. This study considers electricity and hot water as energy demands of the households because space cooling and heating are supplied by electric air conditioners installed at each household.

In IC, electricity generated by the H-GCGSs is shared among the households in the housing complex; however, the generated electricity is not transmitted to an external commercial electric power system. Thus, electricity is supplied to meet the electric demands of the households by operating the H-GCGSs and by purchasing electricity in bulk from an electric power company. Generated electricity is also provided to drive the auxiliary machines of the H-GCGSs. This power interchange operation has little influence on the stability of the electric power system because electricity generated by each H-GCGS is synchronized with the electric power system through an inverter for voltage and phase conditioning. Exhaust heat from both jacket cooling water and exhaust gas of the GE is recovered as hot water and stored in the ST. Hot water in the ST is independently consumed at each household. The shortage of hot water from the ST is supplemented by the GW. The H-GCGSs are not operated with a heat disposal from the energy-saving viewpoint. In actual operation, a control system, which manages operation of multiple H-GCGSs in response to variations in electricity and hot water demands of object households and stored heat in STs, and on-off accessory for each H-GCGS are required, although they are

relaxed. As a result, each H-GCGS under the power interchange operation can operate to meet heat demand variations and to minimize the heat loss from the ST. In addition, there is hardly any electric transmission loss in the housing complex. Hence, the

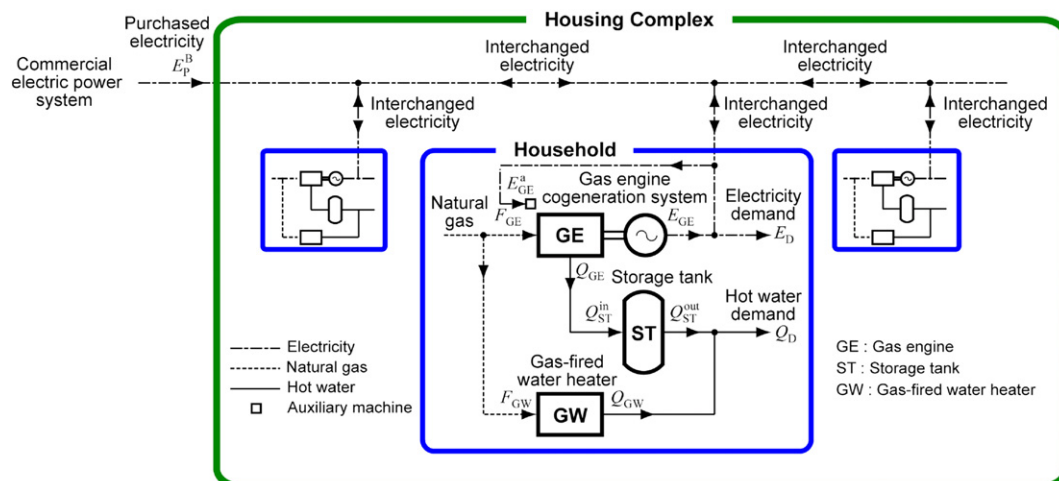


Fig. 1. Schematic diagram of power interchange operation of H-GCGSs.

not considered in this study because the energy-saving effect is evaluated for the feasibility study of IC. Thus, on-line control method for IC must be developed separately for the practical use.

This study also considers two other types of household energy supply configurations to evaluate the energy-saving effect of IC. One is stand-alone operation of each H-GCGS without the power interchange among the household (SA). This is the only operation method of the H-GCGS permitted in Japan. The other is conventional energy supply system without the H-GCGS (CO): electricity is supplied only by purchased one from the electric power company, and hot water is supplied only by the GW.

3. Optimal operational planning problem

The energy-saving effect of IC is evaluated using an optimization approach based on the mixed-integer linear programming. That is, the optimal operational strategies of the three types of household energy supply configurations including on-off and rated-partial load status of the operation of the system components, energy flow rates, and stored heat are determined to minimize primary energy consumption subject to the satisfaction of energy demand requirements. This optimal operation planning problem is described below.

3.1. Mathematical formulation

The housing complex investigated in this study has N households, and the index for the households is designated by n , i.e., $n = 1, 2, \dots, N$. Moreover, to consider seasonal and hourly changes in the energy demands, a typical year is divided into M representative days. The index for the representative days is designated by m , i.e., $m = 1, 2, \dots, M$. Furthermore, each representative day is divided into K sampling times with a period of Δt , i.e., $\Delta t = 24/K$. The index for the sampling times is designated by k , i.e., $k = 1, 2, \dots, K$. The operational strategy of a cogeneration system with a ST cannot be determined independently for each sampling time. Thus, the daily cyclic operation, which assumes that energy demands change cyclically with a period of 24 h on each representative day, is considered [8].

3.1.1. Decision variables

The decision variables are composed of binary and continuous variables. The binary variable expresses the on-off status of the operation of the H-GCGS of the n th household at the k th sampling time on the m th representative day. The continuous variables express the flow rates of the input and output energies of the system components and stored heat in the ST in the same condition as that of the binary variables.

3.1.2. Objective function

The objective function J to be minimized is the total daily primary energy consumption of the object households on each representative day in order to evaluate the energy-saving effect. The definition of the total daily primary energy consumption depends on the household energy supply configurations.

First, for IC, the objective function J_{IC} on the m th representative day is expressed by the following equation:

$$J_{IC}(m) = \varphi_G \sum_{k=1}^K \left[\sum_{n=1}^N F_{GE}(n, k, m) + \sum_{n=1}^N F_{GW}(n, k, m) \right] \Delta t + \varphi_E \sum_{k=1}^K E_p^B(k, m) \Delta t \quad (m = 1, 2, \dots, M) \quad (1)$$

where φ_G and φ_E denote the conversion factors for the primary energy of natural gas and electricity, respectively; F_{GE} and F_{GW}

denote the natural gas consumption of the H-GCGS and GW, respectively; and E_p^B denotes the electricity purchased in bulk. For SA, the objective function J_{SA} is expressed by the following equation:

$$J_{SA}(m) = \varphi_G \sum_{k=1}^K \left[\sum_{n=1}^N F_{GE}(n, k, m) + \sum_{n=1}^N F_{GW}(n, k, m) \right] \Delta t + \varphi_E \sum_{k=1}^K \sum_{n=1}^N E_p^I(n, k, m) \Delta t \quad (m = 1, 2, \dots, M) \quad (2)$$

where E_p^I denotes the electricity purchased individually at each household. For CO, the objective function J_{CO} is expressed by the following equation:

$$J_{CO}(m) = \varphi_G \sum_{k=1}^K \sum_{n=1}^N F_{GW}(n, k, m) \Delta t + \varphi_E \sum_{k=1}^K \sum_{n=1}^N E_p^I(n, k, m) \Delta t \quad (m = 1, 2, \dots, M) \quad (3)$$

3.1.3. Constraints

The constraints in this optimization problem are composed of the performance characteristics of the system components and energy balance and supply-demand relationships.

The H-GCGSs adopt the on-off operation, which implies either rated load operation or shutdown [2,7]; this is attributed to the characteristic that the partial load operations of the small-scale GEs are inefficient. Thus, the generated electricity E_{GE} , heat flow rate of recovered hot water Q_{GE} , natural gas consumption F_{GE} , and electricity consumed by the auxiliary machine E_{GE}^a are expressed as follows:

$$\left. \begin{aligned} E_{GE}(n, k, m) &= p_{GE} \delta_{GE}(n, k, m) \\ Q_{GE}(n, k, m) &= q_{GE} \delta_{GE}(n, k, m) \\ F_{GE}(n, k, m) &= r_{GE} \delta_{GE}(n, k, m) \\ E_{GE}^a(n, k, m) &= s_{GE} \delta_{GE}(n, k, m) \\ \delta_{GE}(n, k, m) &\in \{0, 1\} \end{aligned} \right\} \quad (n = 1, 2, \dots, N; k = 1, 2, \dots, K; m = 1, 2, \dots, M) \quad (4)$$

where δ_{GE} denotes the binary variable expressing the on-off status of the operation of the H-GCGS; the coefficients p_{GE} , q_{GE} , r_{GE} , and s_{GE} denote the performance characteristic values of the H-GCGS.

For the STs, the heat balance is considered by the following difference equation:

$$\frac{S_{ST}(n, k, m) - S_{ST}(n, k-1, m)}{\Delta t} = Q_{ST}^{in}(n, k, m) - Q_{ST}^{out}(n, k, m) - \eta_L \Delta t S_{ST}(n, k-1, m) \quad (n = 1, 2, \dots, N; k = 1, 2, \dots, K; m = 1, 2, \dots, M) \quad (5)$$

where S_{ST} denotes the heat stored in the ST; Q_{ST}^{in} and Q_{ST}^{out} denote the heat flow rates of hot water stored into and supplied from the ST, respectively; η_L denotes the heat loss rate of the ST. Moreover, the heat stored in the ST is limited by its capacity $\bar{S}_{ST}$ as follows:

$$0 \leq S_{ST}(n, k, m) \leq \bar{S}_{ST} \quad (n = 1, 2, \dots, N; k = 0, 1, \dots, K; m = 1, 2, \dots, M) \quad (6)$$

Under the assumption that the ST is cyclically used with a period of 24 h, the heat stored at the initial state is equal to that at the terminal state at each household on each representative day.

Table 1
Performance characteristic values of system components

Equipment	Performance characteristic value
Gas engine cogeneration system	$p_{GE} = 1.0 \text{ kW}$ $q_{GE} = 3.7 \text{ kW}$ $r_{GE} = 0.443 \text{ m}^3/\text{h}$ $s_{GE} = 0.075 \text{ kW}$
ST	$\overline{S_{ST}} = 30.1 \text{ MJ}$ $\eta_L = 1.0\%/h$
GW	$q_{GW} = 36.0 \text{ MJ}/(\text{m}^3/\text{h})$

$$S_{ST}(n, 0, m) = S_{ST}(n, K, m) \quad (n = 1, 2, \dots, N; m = 1, 2, \dots, M) \quad (7)$$

For the GWs, the relationship between the heat flow rates of supplied hot water Q_{GW} and the natural gas consumption F_{GW} are expressed by the following equations:

$$\left. \begin{aligned} Q_{GW}(n, k, m) &= q_{GW} F_{GW}(n, k, m) \\ 0 &\leq F_{GW}(n, k, m) \end{aligned} \right\} \quad (n = 1, 2, \dots, N; k = 1, 2, \dots, K; m = 1, 2, \dots, M) \quad (8)$$

where the coefficient q_{GW} denotes the performance characteristic value of the GW.

Furthermore, the energy balance and supply–demand relationships for electricity and hot water are considered. The

electricity balance and supply–demand relationships depend on the household energy supply configurations: for IC, it is considered in the housing complex; for SA and CO, it is considered at each household. On the other hand, the hot water balance and supply–demand relationships are considered at each household in any household energy supply configuration.

3.2. Solution method and its validity

The optimal operational planning problem formulated in the previous section results in a mixed-integer linear programming problem. This is solved by the GAMS (General Algebraic Modeling System)/CPLEX solver, which is a general-purpose solver that combines the branch and bound method with the simplex one for large-sized mixed-integer linear programming problems [9]; thus, optimal operational strategies calculated by this solver have high accuracy.

4. Numerical study

A numerical study on the energy-saving effect of IC is conducted using the aforementioned optimization model. First, the input data for this optimization problem are described; then, the energy-saving effect of IC is discussed through a numerical analysis of optimal operational strategies.

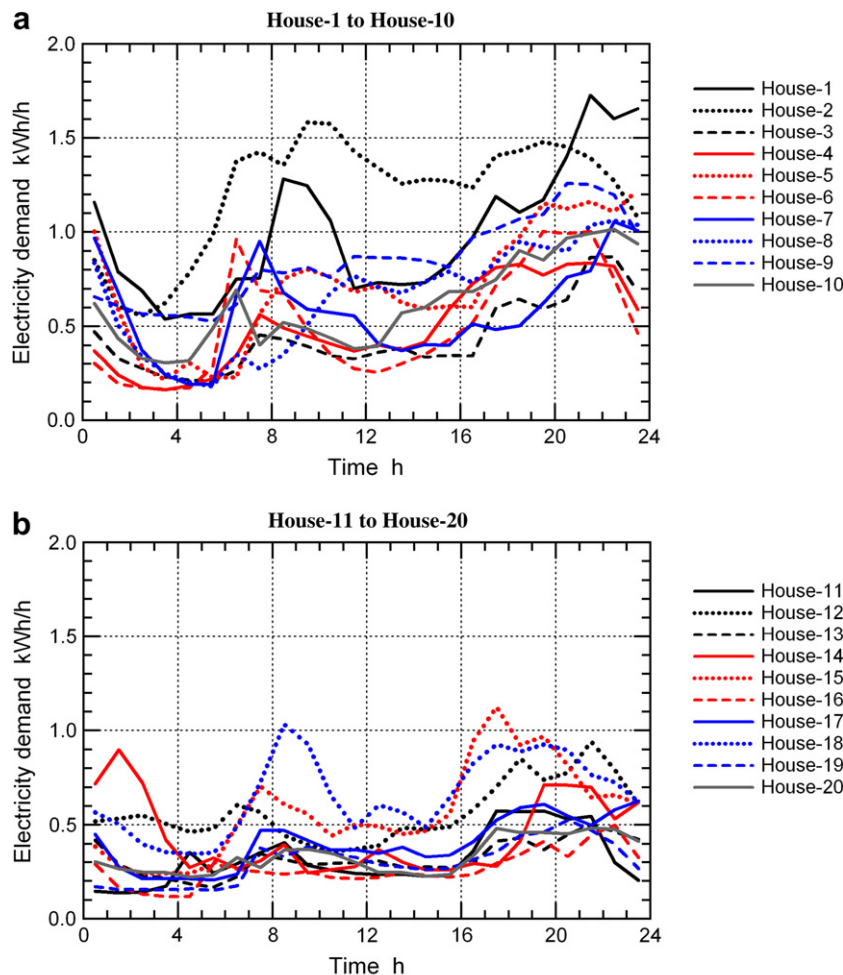


Fig. 2. Hourly electricity demands at 20 households in December. (a) House-1 to house-10, (b) house-11 to house-20.

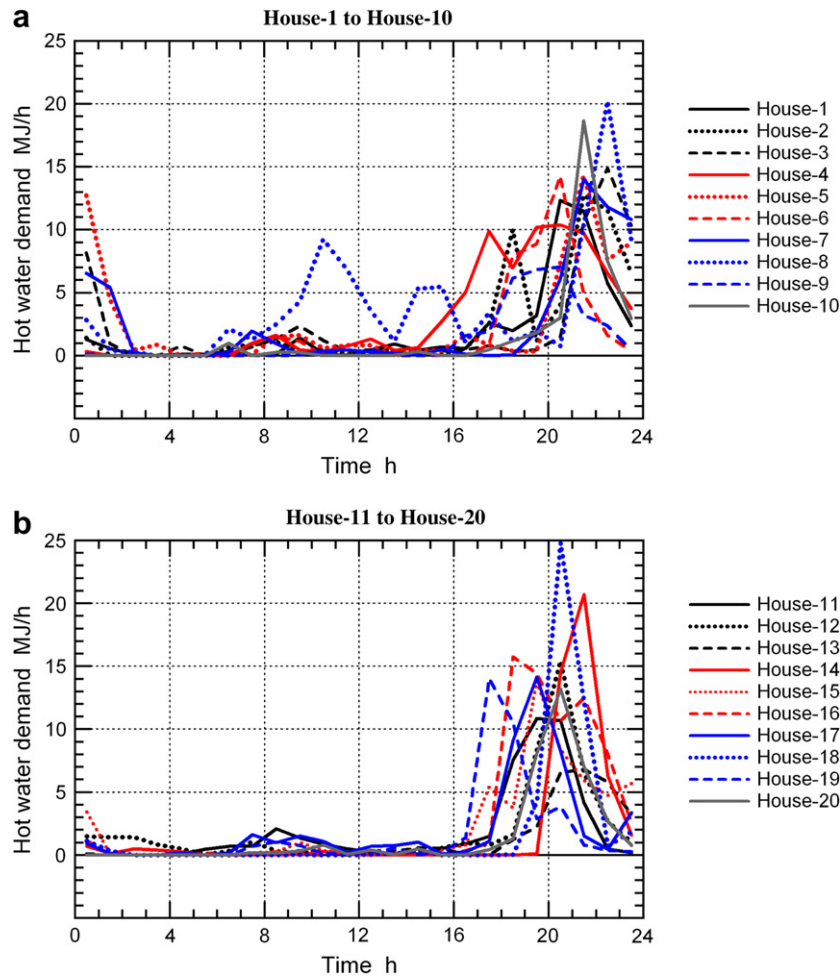


Fig. 3. Hourly hot water demands at 20 households in December. (a) House-1 to house-10, (b) house-11 to house-20.

4.1. Input data

The input data for this optimization problem are composed of the performance characteristic values of the system components, household energy demands, and conversion factors for primary energy.

The performance characteristic values of the system components are listed in Table 1. These values are derived from Refs. [7] and [10] and our actual operating performance. The net generating efficiency considering the electricity consumed by the auxiliary machine and heat recovery efficiency of the H-GCGS and thermal efficiency of the GW calculated using the higher heating value of natural gas are about 17%, 67%, and 80%, respectively.

The housing complex investigated in this study has 20 households, i.e., $N = 20$. The energy demands at the 20 households are estimated at 24 sampling times for a representative day of each month, i.e., $M = 12$, $K = 24$, and $\Delta t = 1$ h. The electricity and hot water demands at the 20 households have been measured by Tsuji et al. [11]. As examples of the energy demand patterns, Figs. 2 and 3 show the hourly electricity and hot water demands at the 20 households on the representative day of December, respectively.

Table 2
Conversion factors for primary energy

Energy source	Value
Electricity	$\varphi_E = 9.83 \text{ MJ/kWh}$
Natural gas	$\varphi_G = 45.0 \text{ MJ/m}^3$

The hourly electricity demands differ widely among the 20 households. Moreover, the period when the electricity demand exceeds the net generated electricity of the H-GCGS is limited at any household. On the other hand, the hot water demands are concentrated in the nighttime at any household.

The conversion factors for primary energy are listed in Table 2. For electricity, the thermal power average conversion factor defined in the Law Concerning the Rational Use of Energy of Japan is introduced.

4.2. Results and discussion

4.2.1. Energy-saving effect of power interchange operation for five households

The energy-saving effect of IC is discussed through the numerical analysis of the optimal operational strategies. First, the energy-saving effect of IC for five of 20 object households, which are called as House-1 to -5 for convenience, i.e., $N = 5$, is investigated. Their energy demands are shown in Figs. 2 and 3.

Figs. 4 and 5 show the optimal operational strategies using IC and SA on the representative day of December, respectively. The optimal operational strategy for the electricity supply using IC shows the total electricity supply to the five households, and the other optimal operational strategies show the energy supply only to House-3. As shown in Fig. 5, the H-GCGS at House-3 cannot be operated in SA because the electricity demand at House-3 is less than the net generated electricity of the H-GCGS throughout the day. Therefore, all hot water is supplied by the GW. On the other

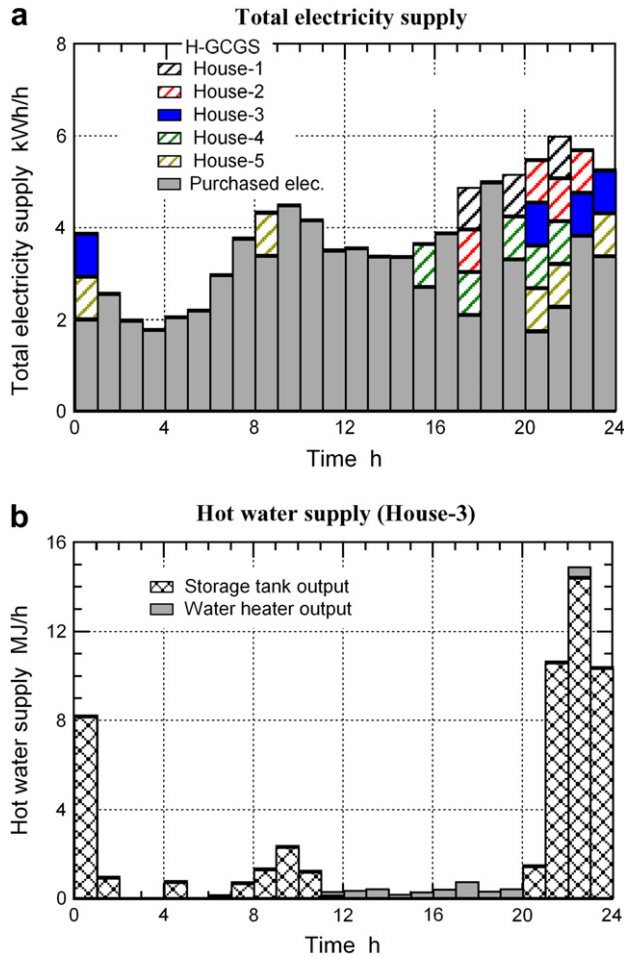


Fig. 4. Optimal operational strategy using IC in December. (a) Total electricity supply, (b) hot water supply (house-3).

hand, the H-GCGS at House-3 in IC can operate for 4 h because the total electricity demand of the object households becomes larger than the net generated electricity of the H-GCGS. Thus, IC relaxes the operational restriction of the H-GCGS in SA and increases the operating time of the H-GCGSs. In this case, most of hot water is supplied from the ST. Moreover, the operation of the H-GCGSs in IC is concentrated in the nighttime so that the heat losses from the STs may be minimized. This operational strategy contributes to the reduction in the natural gas consumption for the GW.

Table 3 lists the computational result of the total daily purchased electricity, and the total daily natural gas and primary energy consumptions of the five households on the representative day of December for the three types of household energy supply configurations. By the introduction of the H-GCGSs (IC, SA), the total daily natural gas consumption of the five households increases whereas the total daily purchased electricity decreases. These are because of operation of the H-GCGSs. As a result, the total daily primary energy consumptions in IC and SA are less than that in CO. Furthermore, the total daily primary energy consumption in IC is lower than that in SA owing to the increase in the operating time of the H-GCGSs in IC.

4.2.2. Effect of increasing number of object households

On the basis of the result for the five households, the energy-saving effect due to increasing the number of object households is investigated.

Fig. 6 shows the optimal operational strategies for the total electricity supply using IC on the representative day of December at

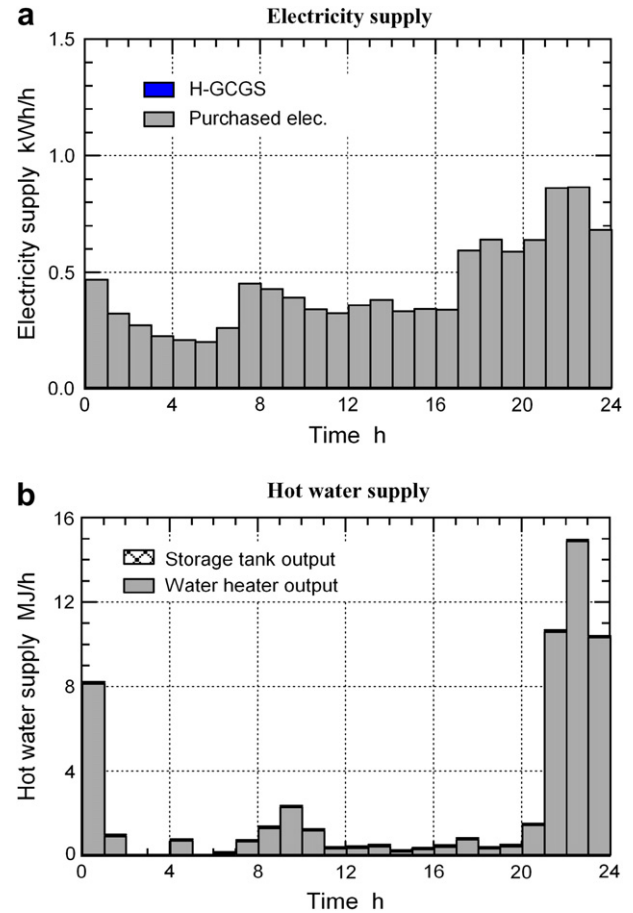


Fig. 5. Optimal operational strategy using SA at House-3 in December. (a) Electricity supply, (b) hot water supply.

10 (House-1 to -10), 15 (House-1 to -15), and 20 households (House-1 to -20), i.e., $N = 10, 15, 20$. For any number of the object households, the operation of the H-GCGSs is concentrated in the nighttime when the hot water demand increases. Moreover, by analyzing the optimal operational strategies for the hot water supply, it is confirmed that most of hot water is supplied from the ST at any household.

To evaluate the energy-saving effect of IC, the reduction rates in the total daily primary energy consumption from CO to IC $\alpha_{IC/CO}$ and those from SA to IC $\alpha_{IC/SA}$ for four cases of the number of the object households, i.e., $N = 5, 10, 15, 20$, on the representative days of August, October, and December are listed in Table 4. $\alpha_{IC/CO}$ and $\alpha_{IC/SA}$ on the m th representative day are defined as follows:

$$\alpha_{IC/CO}(m) = \frac{J_{CO}(m) - J_{IC}(m)}{J_{CO}(m)} \times 100 \quad (m = 1, 2, \dots, M) \quad (9)$$

$$\alpha_{IC/SA}(m) = \frac{J_{SA}(m) - J_{IC}(m)}{J_{SA}(m)} \times 100 \quad (m = 1, 2, \dots, M) \quad (10)$$

Table 3

Total daily purchased electricity, and total daily natural gas and primary energy consumptions of five households in December

Energy supply configuration	IC	SA	CO
Total purchased electricity, kWh/d	73.3	81.6	92.7
Total natural gas consumption, m ³ /d	9.87	9.18	8.23
Total primary energy consumption, MJ/d	1165	1215	1282

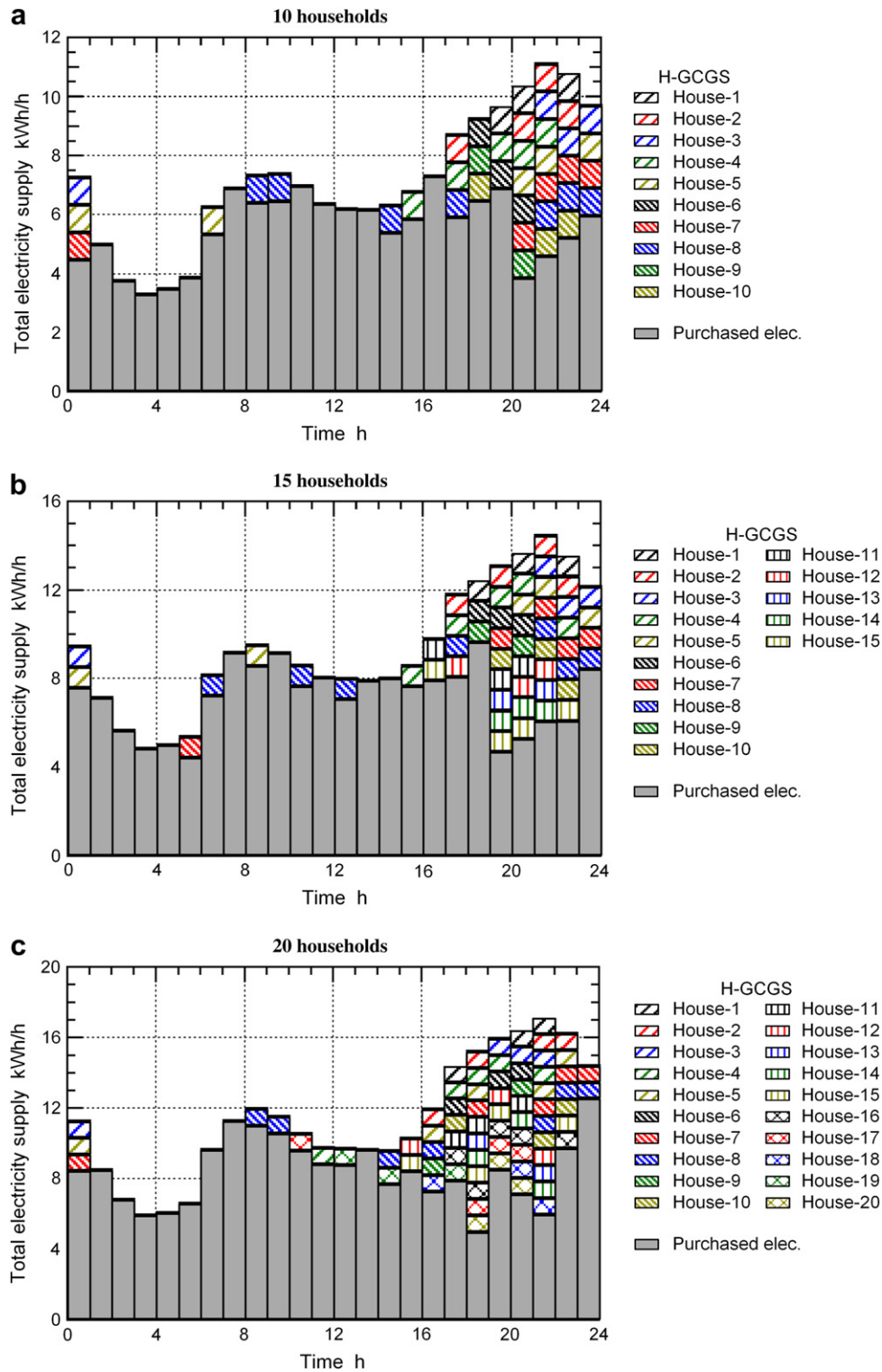


Fig. 6. Optimal operational strategy for total electricity supply using IC in December. (a) 10 households, (b) 15 households, (c) 20 households.

where J_{CO} , J_{SA} , and J_{IC} denote the total daily primary energy consumption in CO, SA, and IC, respectively.

Obviously, IC has a higher energy-saving effect than SA and CO on any representative day and for any number of the object households. The increase of $\alpha_{IC/CO}$ is outstanding in December where the operating time of the H-GCGSs increases strikingly owing to more hot water demand, while $\alpha_{IC/SA}$ increases in October and December. However, there is no definite correlation between the two types of the reduction rates and the number of the object households. The

aforementioned result of the optimal operational strategy for the five households indicates that the energy-saving by IC mainly results from the increase in the operating time of the H-GCGSs at the households that have less electricity demand. Thus, the energy-saving effect of IC is not affected by the number of the object households but affected by the energy demand patterns of the object households.

To clarify a dominant parameter to characterize the energy-saving effect of IC, the relationship between the two types of the

Table 4

Reduction rate of total daily primary energy consumption for four cases of number of object households on three representative days

Reduction rate of total daily primary energy consumption α %						
Month	August		October		December	
Comparative configuration	IC/CO	IC/SA	IC/CO	IC/SA	IC/CO	IC/SA
5 households	3.32	1.08	6.65	3.16	9.14	4.17
10 households	2.60	1.02	6.38	3.60	9.33	3.51
15 households	2.70	1.19	6.48	4.36	9.64	4.42
20 households	2.86	1.22	7.08	5.52	10.04	5.62

reduction rates in the primary energy consumption and the total daily heat to power demand ratio of the object households (THPR) is examined. THPR on the m th representative day is defined as the ratio of the total daily hot water demand of the object households to their total daily electricity demand as follows:

$$\text{THPR}(m) = \frac{\sum_{k=1}^K \sum_{n=1}^N Q_D(n, k, m) \Delta t}{\sum_{k=1}^K \sum_{n=1}^N E_D(n, k, m) \Delta t} \quad (m = 1, 2, \dots, M) \quad (11)$$

where E_D and Q_D denote the demand of electricity and hot water of the n th household at the k th sampling time on the m th representative day, respectively.

The numerical result of the relationship based on the optimal operational strategy on the representative day of each month is shown in Fig. 7. $\alpha_{IC/CO}$ increases almost linearly with THPR; therefore, the energy-saving effect by introducing IC can be evaluated using THPR. On the other hand, $\alpha_{IC/SA}$ tends to increase with THPR; however, there is no clear correlation between $\alpha_{IC/SA}$ and THPR. Since the relaxation of the operational restriction by IC is affected by the energy demand patterns of the object households, a detailed analysis of the energy demand patterns is required to investigate a dominant parameter to characterize $\alpha_{IC/SA}$ that is the criterion to determine the energy supply configuration using the H-GCGS.

4.2.3. Difference between actual energy-saving effect and optimal result

The abovementioned optimal results are computed under the condition where the energy demands of the object households are preliminarily determined. This means that the predicted result of the household energy demands totally coincides with the actual one. Thus, the energy-saving effect of the H-GCGSs under actual operation may be lower than the optimal result due to uncertainty of the energy demand prediction. However, it is considered that the decrease in the actual energy-saving effect in IC may be less than that in SA. This is because a prediction error rate of the total electricity demand of object households, which becomes the electric load to each H-GCGS in IC, can be smaller than that of each household owing to offsetting of prediction error at each household.

Furthermore, the sampling period of the energy demands Δt also has a significant influence on the energy-saving effect of the H-GCGSs derived from an optimization model because actual household energy demands generally have fluctuations with short periods due to the use of appliances. Hawkes and Leach reported that CO₂ reduction effect of household cogeneration systems in SA is overestimated by analyses conducted using the sampling period of 1 h [12]. Thus, the energy-saving effect of SA in this study may be also overestimated; however, it is considered that the overestimation of the energy-saving effect of IC may be smaller than that of SA. This is because the fluctuation of electricity demand at each household is smoothed by evaluating the total electricity demand of the object households in IC.

Therefore, IC is expected to have an advantage in the decrease in the energy-saving effect under actual operation over SA.

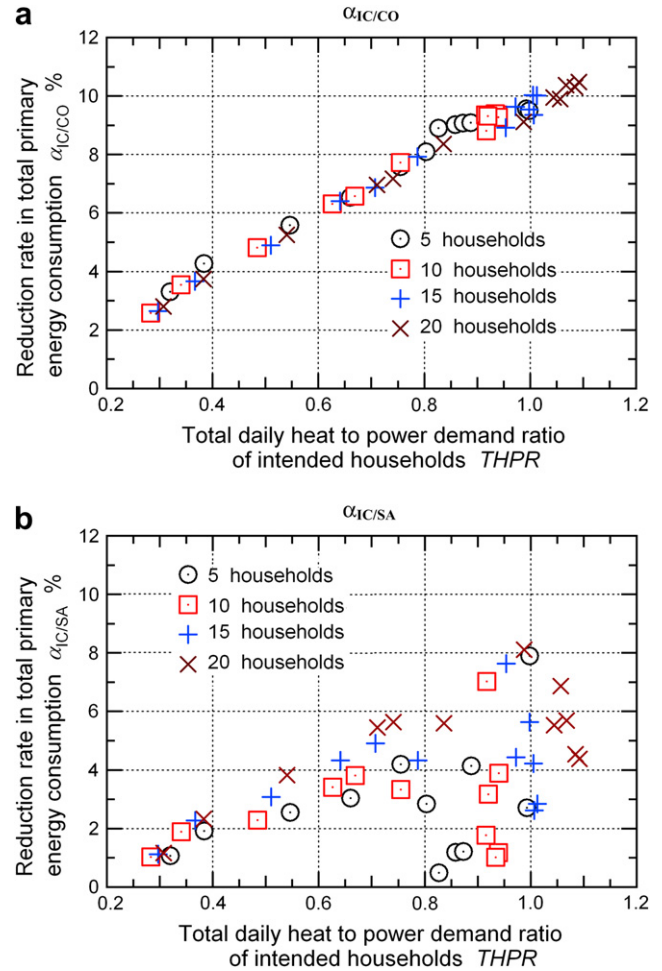


Fig. 7. Relationship between reduction rate in total primary energy consumption and THPR in each month. (a) $\alpha_{IC/CO}$, (b) $\alpha_{IC/SA}$.

5. Conclusions

The energy-saving effect of power interchange operation of multiple household gas engine cogeneration systems (H-GCGSs) in a housing complex has been investigated by an optimization approach as the first step of its feasibility study. In the power interchange operation, electricity generated by the H-GCGS is shared among households in the housing complex without transmitting to an external commercial electric power system. A numerical analysis of optimal operational strategies by the mixed-integer linear programming has been conducted for 20 households and three types of household energy supply configurations: the power interchange operation of the multiple H-GCGSs (IC), stand-alone operation of each H-GCGS (SA), and conventional energy supply system without the H-GCGSs (CO). The results obtained in this study are summarized as follows:

- IC increases the operating time of the H-GCGS and enables their operation so that the heat loss from the ST may be minimized.
- IC is the most effective in the energy-saving among the three types of the household energy supply configurations in any season for any number of the object household.
- There is no correlation between the energy-saving effect of IC and the number of the object households.
- The energy-saving effect from CO to IC can be evaluated with the THPR.

These results clarify the energy-saving effect of IC in the housing complex in the area where electricity generated by household cogeneration systems cannot be transmitted to commercial electric power systems. As future tasks, the authors will investigate a dominant parameter to characterize the energy-saving effect of IC against SA through a detailed analysis of the energy demand patterns of the object households. Furthermore, the authors recognize the importance of financial benefit by the H-GCGSs. However, in order to conduct the feasibility study from the economic viewpoint, the information including the periodic maintenance cost, additional cost of a control system for the power interchange operation, and utility charge structure for the power interchange operation in a housing complex as well as the initial cost of the H-GCGS must be required. Thus, this feasibility study is considered as the second step of our study.

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